Spectral Characteristics of Rice Canopy with Infestations of Leaf Folder and Brown Planthopper

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ABSTRACT

Potted experiments of rice plants (*Oryza sativa* L. cv. Tainung 67) were conducted at Taiwan Agricultural Research Institute to produce various rankings of brown planthopper [*Nilaparvata lugens* (Stål) or Homoptera:Delphacidae] or leaf folder infestations (*Cnaphalocrosis medinalis*) for canopy high-resolution spectral measurements, and then to identify spectral characteristics in associated with pest infestations leading to the establishment of remote sensing models for future applications. Reflectance spectra were taken by a field-portable spectroradiometer near ground and infestations by the pests were classified into six scales, i.e., 0 (healthy check), 1, 3, 5, 7 and 9, based on the percentages of damaged canopies. By correlation intensity analysis of spectral reflectance and infestation ranking, correlation coefficients along the measured spectral domain were determined to select spectral characteristics of the reflectance spectra. For brown planthopper infested canopies, reflectance (narrow band) at 426 nm had the highest value of correlation coefficient ($r=0.878^{**}$). However, the quadratic function of single reflectance at 1450 nm improved the coefficient of determination (R^2) up to 0.857 ($P<0.01$). Among the calculated spectral indices with two spectral characteristics, six indices had R^2 greater than 0.82, especially R_{RED}/R_{NIR} ratio ($R^2=0.908$, $P<0.001$). For leaf folder infested canopies, spectral characteristics selected at near-infrared (740-1300 nm) peak (R_{NIR}) and blue light (425-490 nm) minimum (R_{BLUE}) had the highest values of R^2 (0.376 and 0.871) for measurements conducted in the tillering stage and heading stage, respectively. The reflectance difference R_{NIR}-R_{RED} in the tillering stage increased R^2 value to 0.422 ($P<0.001$), while R_{NIR}/R_{RED} ratio promoted R^2 value to 0.662 ($P<0.001$) in the heading stage, where R_{RED} is the reflectance at red light (640-740 nm) minimum. Models established by the multiple linear regression (MLR) analysis exhibited a further improvement to discriminate infestation ranking. The best six-variable MLR model improved R^2 value to 0.856 ($P<0.0001$) for the tillering stage measurements, and the best four-variable MLR model can increase R^2 value to 0.960 ($P<0.0001$) for the heading stage measurements.

Key words: Spectral characteristics, Reflectance spectrum, Rice canopy, Brown planthopper (*Nilaparvata lugens*), Leaf folder (*Cnaphalocrosis medinalis*).

INTRODUCTION

Reflectance spectrum of a plant population is known to be a function of canopy optical properties which contributed from biophysical and biochemical attributes of vegetation, viewing geometry of detector, illumination conditions of surrounding, and background effects (Asner, 1998; Barrett and Curtis, 1992; Goel, 1988; Jacquemoud *et al.*, 1992; Myneni *et al.*, 1989; Ross, 1981). The three-dimensional orientation of biophysical attributes of vegetation provides a better architecture for photons reception from incident radiation yet creates variation in the spectral characteristics. The biochemical components of plant parts bring into influences on the tissue optical nature (Baret *et al.*, 1994; Goward and Huemmrich, 1992; Jacquemoud, 1993; Kupiec and Curran, 1995). Weeds and pest infestations produce additional interference and cause difficulties in spectral discrimination between species. In fact changes of any individual or combination of elements that affect the reflection of light from a complex vegetative surface may alter the spectral pattern of vegetation.

Techniques of multi-spectral remote sensing have been applied to monitoring crop growth status for various purposes (Bauer, 1975; Bausch *et al.*, 1994; Cloutis *et al.*, 1996; Fernandez *et al.*, 1994; Shibayama and Akiyama, 1991; Walburg *et al.*, 1982; Wallace *et al.*, 1993). Due to a lack of high spectral resolution, the spectral responses of crop conditions may mix with various factors occurring at the same time (Carter, 1993; Malthus and Madeira, 1993; Tingle and Stoll, 1990), and hence limit the uses of the techniques. The development of hyperspectral remote sensing has satisfied the demand in providing qualitative and quantitative details of vegetation spectrum and in helping to assess and evaluate crop condition parameters (Blackburn, 1998; Ferns *et al.*, 1984; Yoder and Pettigrew-Crosby, 1995). In a pest infested field, the spatial variability of pest infestations obtained from analyzing hyperspectral data offers a better understanding of field conditions for site-specific pest management. The correct amount of pesticides can then be applied to the exact places at the right time. However, such applications require pre-established ground truths linkage for data verification and validation so that future practices can be directed more efficiently and economically.

Brown planthopper, *Nilaparvata lugens* (Stål), (Homoptera:Delphacidae), is considered to be a serious insect pest in many rice-producing regions including Taiwan. It is used to be the most prevalent pest island-wide bringing about destructive damage each year to rice crops (Ho and Liu, 1969; Cheng, 1978, 1990; Cheng and Lu, 1991). Rice leaf folder [*Cnaphalocrosis medinalis* Guenee (Lep., Pyralidae)], or called rice leafroller (Cheng, 1978; Miyahara, 1981; Hirao, 1982), is a widely distributed pest over Asia (Hirao, 1982)as well as a long-term major rice pest in Taiwan (Taiwan Provincial Department of Agriculture and Forestry, 1985). Leaf rolling occurs in early stages of infestation and whitish discoloration follows later. Under serious infestations, both pests cause yield reduction. If there are available information on the exact field location and levels of infestations of pest outbreaks, farmers could target pesticides applications specifically to the designated field spots where the pests are present. In this sense hyperspectral remote sensing is a suitable means to investigate spectral characteristics of rice canopy infested with pests, as the brownish and whitish discoloration appearing on the upper surface of the canopy are expected to be detected. To play an effective role in managing these pests, relationships between spectral characteristics and symptoms of infestations must be adequately investigated based on ground studies prior to the development of the management schemes.

This study took the remotely sensed high-resolution reflectance spectra of rice canopy near ground and analyzed the spectral characteristics of the infested plants. Spectral indices and regression models showing correlation with symptoms of infestation were also determined for future assessment of the plants responsive to pest infestations.

MATERIALS AND METHODS

The 8-d old seedlings of rice cultivar Tainung 67 (*Oryza sativa* L.) were transplanted to opaque plastic containers, one plant per container, with a diameter of 0.32 m and a height of 0.2 m in the first cropping seasons of 2000 and 2003. The soil was a sandy loam with a pH of 7.24. Potted plants were fertilized with ammonium sulfate at a rate of 4 g pot^{-1} as the basal dose, and two additional doses were applied within 3-wk after transplanting and 2-wk before heading, respectively, using a composite fertilizer TaiFei-39 ($N:K_2O:P_2O_5$= 12:18:12, Taiwan Fertilizer Company, Kaohsiung, Taiwan), both at a rate of 12 g pot^{-1}. Pots were kept at the experimental farm of the Chiayi Branch Station (120°27′15″E, 23°29′10″N, elevation of 35 m) of the Taiwan Agricultural Research Institute (TARI). Weeds were removed by hand-weeding and water was irrigated daily as scheduled. When reached the early grain-filling stage, 8 June 2000 and 3 June 2003, groups of pots with similar growth status and same ranking of brown planthopper infestations were selected for spectral measurements. There were 6 rankings of plant damage as that defined in Table 1. Symptoms ranged from partial to pronounced yellowing and low to high severity of stunting (INGER Genetic Resources Center, 1996). In extreme cases, symptoms observed ranged from wilting to death of plants. Reflectance spectra from years were examined and pooled for analyses.

As climatic conditions in the second cropping season are generally favorable to the infestation of rice leaf folder (Taiwan Provincial Department of Agriculture and

Table 1. Rankings of rice plant damage by the infestations of brown planthopper [*Nilaparvata lugens* (Stål)].

Ranking	Symptom
0 (CK)	No damage
1	Slight yellowing of a few plants
3	Leaves partially yellow but with no hopperburn
5	Leaves with pronounced yellowing and some stunting or wilting and 10-25% of plants with hopperburn, remaining plants severely stunted
7	More than half the plans wilting or with hopperburn, remaining plants severely stunted
9	All plant dead

Source: INGER Genetic Resources Center (1996).

Forestry, 1985), this pest has been considered a major target for pests control in the second crops in Taiwan. In the second experiment, similar cultivation practices were applied to grow rice plants in the plastic containers during the second cropping season of 2001. Dates of seedlings preparation were adjusted so that two sets of potted plants were grown to active tillering stage and heading stage, respectively. Each set of plants was infested to 6 rankings of plant damage as that listed in Table 2, and the reflectance spectra of different rankings from each set of potted plants were taken on the same day.

Table 2. Rankings of rice plant damage by the infestations of leaf folder (*Cnaphalocrosis medinalis*).

Ranking	Percentage of leaves infested (%)
0 (healthy check)	0
1	1-10
3	11-25
5	26-35
7	36-50
9	>50

Full-range (330-2600 nm) hemispherical reflectance values of targeted plants were obtained on the ground using a battery-operated field portable spectroradiometer (model GER-2600, Geophysical & Environmental Research Corp., Millbrook, New York, USA) having a 10° field-of-view (FOV) detector lens. The unit was supported by a tripod approximately 1.8 m above the canopy surface resulted in a 0.3 m diameter target area. All spectral measurements, calibrations, and graphic displays for the instrument were controlled by simple menu driven software program on a notebook computer (GER 2600 User Manual, 1996). Modes of radiance, irradiance, and percent reflectance were available for interpretation of the data. Reflectance spectrum were obtained by comparing the radiance of the target plants with the radiance of a standard reference panel, the so-called 'Spectralon' (Labsphere, Inc., North Sutton, NH, USA) for known spectral characteristics. Target and reference scans were conducted successively to produce reflectance measurements. The GER-2600 acquires measurements in 1.5 nm intervals in the visible/near-infrared (330-1050 nm) region using a 512-element silicon detector and in 11.5 nm in the wavelength range from 1050 to 2600 nm with a 128-PbS detector array. Only reflectance data in 350-2400 nm range, covering from ultraviolet to mid infrared, were used to avoid noise influences, and the band centers were rounded off to nearest whole number for application purposes (e.g., 550.22 nm as 550 nm).

At least five consistent measurements (spots) were taken from plants of each ranking and each measurement was the mean of three individual full-range spectral scans. All spectra were acquired under clear or cloudless conditions between 10:30 and 11:30 local standard time. As canopy coverage of grouped plants reached more than 90% in a nadir viewing, most parts of reflectance spectrum were found not affected by background effects by spectral comparisons. Nevertheless, care was taken to prevent the influence of shadow and background.

Changes in the spectral reflectance to the rankings of infestations were evaluated by correlation intensity analysis. With the correlation intensity curves, the intensities of linear relationship of the individual

wavebands along the analyzed spectral domain (350-2400 nm) were displayed and the spectral characteristics of interest were selected. Reflectance at three specific locations of the spectrum was also identified for narrow band comparisons and regression analysis to pest infestations. They were chosen from reflectance at the green light (490-560 nm) maximum (R_{GREEN}), the red light (640-740 nm) minimum (R_{RED}), and the near-infrared (740-1300 nm) peak (R_{NIR}). These spectral characteristics are unique in the spectrum, as the results of radiation absorption behavior of plant pigments and optical property of vegetation canopy, and are rather "dynamic" during growth, due to the influences of both internal and external factors as development in progress. Seven ration based spectral indices were also calculated for evaluating differences between rankings of pest infestations, i.e., normalized difference vegetation index (NDVI), green NDVI, soil-adjusted vegetation index (SAVI), R_{RED}-R_{NIR}, and ratios of R_{RED}/R_{NIR}, R_{GREEN}/R_{RED} and R_{NIR}/R_{RED}. The NDVI was determined by the formula $(R_{NIR}-R_{RED})/(R_{NIR}+R_{RED})$ (Elvidge and Chen, 1995) and the SAVI was computed b the formula $(R_{NIR}-R_{RED})*(1+L)/(R_{NIR}+R_{RED}+L)$, where L is defined as 0.5 in this study (Huete, 1988). The green NDVI was obtain by replacing values of R_{NIR} with the values of R_{GREEN}.

The software package Statistical Analysis System (SAS) version 8.1 (SAS, 1998) was adopted for the multiple linear regression (MLR) analysis. Reflectance of narrow bands of the reflectance spectra was used as entry into the Stepwise Selection method at the 0.15 significance level. The selected narrow bands were examined with the Collinearity Diagnostics procedure to avoid a "colliner" phenomenon to sample size. The chosen wavebands were then performed by Stepwise Selection to yield the MLR models. For instance, the best 4-variable model was in the form of $Y_4=a+a_1R_1+a_2R_2+a_3R_3+a_4R_4$, where the dependent variable Y_4 is the ranking of pest infestations and independent variable R_i is reflectance selected from chosen narrow bands of rice reflectance spectrum. The best two or more variables MLR models can be determined with a choice of user-dependent coefficient of determination (R^2) deciding the number of wavebands to be added to the models.

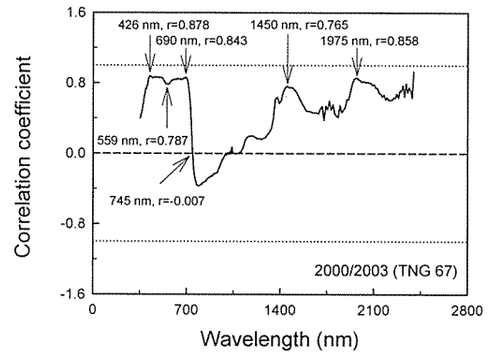

Fig. 1. Linear correlation intensity between spectral reflectance and ranking of brown planthopper infestations for rice plants grown in the early grain-filling stage of the first cropping seasons in 2000 and 2003.

RESULTS AND DISCUSSION

Linear correlation intensity between spectral reflectance and ranking of brown planthopper infestations for rice plants grown in the early grain-filling stage of the first cropping seasons in 2000 and 2003 was plotted in Fig. 1. It showed that correlation coefficient (r) varied along the wavelength

axis with the maximum absolute value located at 426 nm (r=0.878**). In a quadratic correlation, the highest value of determination coefficient (R^2) changed from 426 nm (R^2=0.793, P<0.001) to 1450 nm (R^2=0.856, P<0.001) (Fig. 2). Results indicated that spectral and optical properties and alteration of reflectance were wavelength-dependent, and variation in correlation coefficient was smaller in the visible region (350-740 nm) and higher in the infrared region (740-2400 nm), as that reported by Asner (1998).

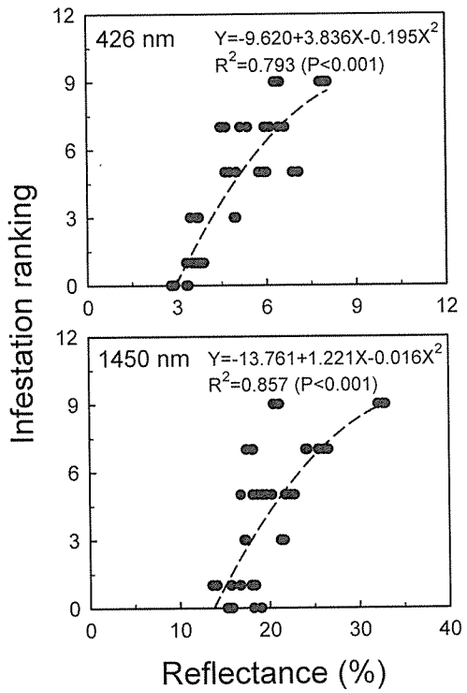

Fig. 2. The quadratic correlation between rankings of brown planthopper infestations and spectral reflectance at 426 nm and 1450 nm, respectively, for rice plants grown in the early grain-filling stage of the first cropping seasons in 2000 and 2003.

Moreover, variability of the symptoms caused by brown planthopper infestations can be accounted for up to about 86% with regression of a single spectral characteristic (1450 nm). With such a high relationship, distinct visual changes in canopy coloration (brownish) and external feature of the infested plants can be expected. The relatively stable spectral properties of rice plants, as that in other studies (Gausman, 1982; Maas and Dunlap, 1989; Walter-Shea and Norman, 1991), in the visible may be attributed to the presence of photosynthetically active pigments. These pigments have two strong absorption bands near blue (450 nm) and red (680 nm) resulting from chlorophyll activity (Salisbury and Ross, 1969). Significant increases in reflectance in the near-infrared (NIR) are due to photon scattering at the air-cell interfaces within the leaf spongy mesophyll (Woolley, 1971; Boyer *et al.*, 1988). The NIR also exhibits the strongest multiple-scattering in the green foliage canopy because of high reflectance plus transmittance of foliage in this region (Asner, 1998; Barrett and Curtis, 1992).

By using spectral indices incorporating with two spectral characteristics to correlate with infestation rankings, R^2 was improved in most indices, especially the exponential function of R_{NIR}/R_{RED} ratio (R^2=0.922, P<0.001) (Fig. 3). In a linear relationship between infestation ranking and value of spectral index, R^2 may increase to 0.908 (P<0.001) using the R_{RED}/R_{NIR} ratio as inputs. Results further suggest that infestations of brown plant hopper would affect the factors involved in pigment absorption (responsive to alteration of R_{RED}) and the vegetation coverage (responsible for fluctuation of R_{NIR}). Usually, reflectance in the green band increases markedly following

the degradation of chlorophyll, while reflectance decreases substantially across the whole range of infrared wavebands due to the changes in the internal structure (Barrett and Curtis, 1992). Accordingly, similar phenomena with respect to the increment in visible reflectance and the reduction in infrared reflectance might occur in rice plants infested with brown planthopper, as that reported in plants infected by a disease (Colwell, 1969; Leeman *et al.*, 1971) and in dehydrated conditions (Aldakheel and Danson, 1997; Rollin and Milton, 1998).

In case of leaf folder-infested rice, pattern of linear correlation intensity was not similar for plants grown in the active tillering stage and in the heading stage (Fig. 4). The linear relationship between spectral reflectance and infestation ranking was negative and was more closely correlated in

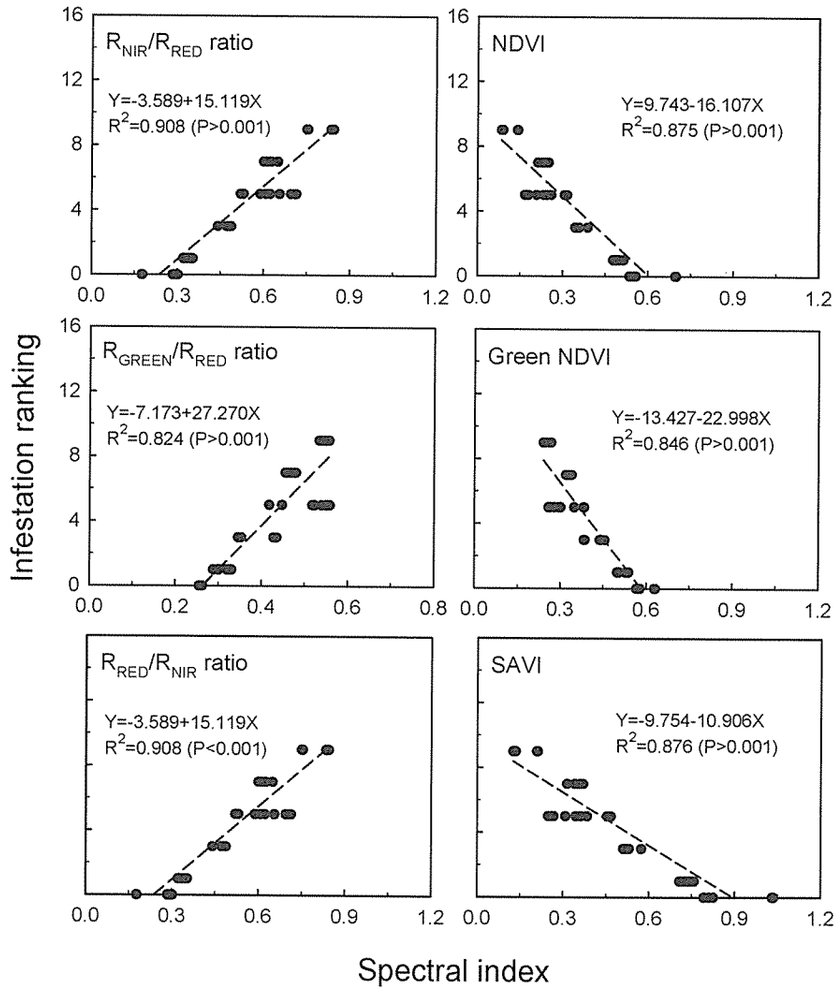

Fig. 3. Changes of infestation rankings to spectral indices in plants of brown planthopper-infested rice grown in the early grain-filling stage of the first cropping seasons in 2000 and 2003.

the heading (r=-0.493 to r=-0.928) than in the active tillering (r=-0.0973 to r=-0.613). The maximum absolute value of correlation coefficient located at 757 nm (r=0.613*) in the active tillering but shifted to 445 nm (r=0.928**) in the heading. The relation of infestation ranking to reflectance was best fitted to a linear function at 757 nm (R^2=0.376, P<0.001) in the active tillering stage yet was best fitted to a quadratic function at 445 nm (R^2=0.881, P<0.001) in the heading stage (Fig. 5). Apparently, the whitish color and leaf rolling symptoms appeared on the vegetative tissues of infested plants did not strongly link to reflectance performance as those shown in the heading period.

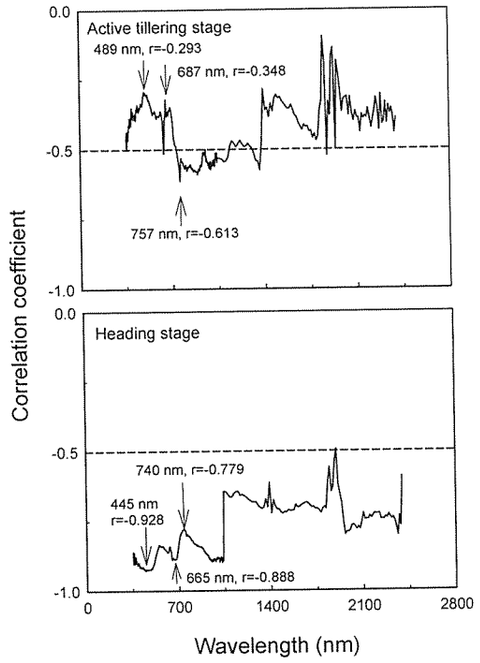

Fig. 4. Linear correlation intensity between spectral reflectance and ranking of leaf folder infestations for rice plants grown in the active tillering and the heading stages of the second cropping season in 2001.

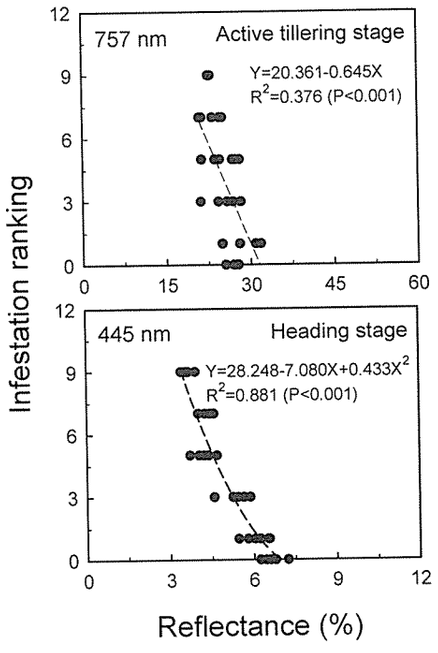

Fig. 5. The relationships between rankings of leaf folder infestations and spectral reflectance at 757 nm and 445 nm for rice plants grown in the active tillering and the heading stages, respectively, of the second cropping season in 2001.

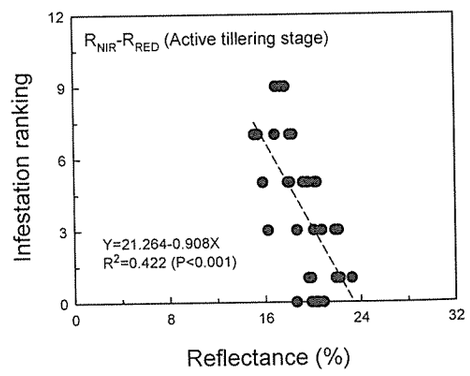

Fig. 6. Changes of infestation rankings to spectral index (R_{NIR}-R_{RED}) in plants of leaf folder-infested rice grown in the active tillering stage of the second cropping season in 2001.

When differentiating rankings of severity with spectral indices, only the reflectance difference between R_{NIR} and R_{RED} was significantly linearly correlated (R^2=0.422, P<0.001) with the infestation ranking in the active tillering stage (Fig. 6). There was a slight increase (0.376 to 0.422) in R^2 from a single spectral characteristic to a two-characteristic index. However, no increase in R^2 was found in the examined spectral indices in the heading stage (Fig. 7). Therefore, the spectral indices calculated by the spectral characteristics R_{GREEN}, R_{NIR} and R_{NIR} have no improvement for the evaluation of rice leaf folder infestations.

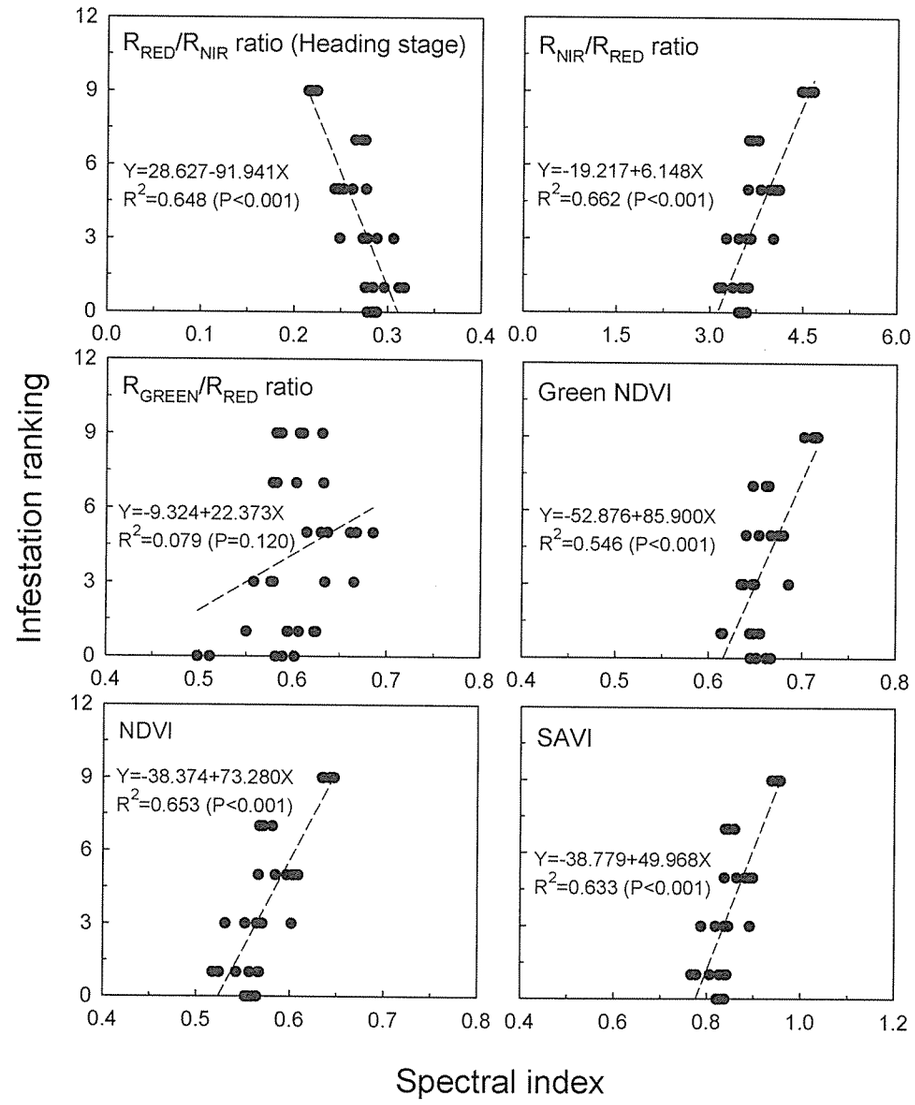

Fig. 7. Changes of infestation rankings to spectral indices in plants of leaf folder-infested rice grown in the heading stage of the second cropping season in 2001.

Table 3. The best six-variable and four-variable linear regression models for evaluation of leaf folder (*Cnaphalocrosis medinalis*) infestations for rice plants (*Oryza sativa* L. cv. TNG 67) grown in the active tillering and the heading stages, respectively, in the second cropping season of 2001.

	$Y_4 = a + a_1R_{\lambda1} + a_2R_{\lambda2} + a_3R_{\lambda3} + a_4R_{\lambda4} + a_5R_{\lambda5} + a_6R_{\lambda6}$									
Growth stage	a	a_1	a_2	a_3	a_4	a_5	a_6	R^2	P	$C_{(P)}$
Active tillering†	27.795	-2.033	-0.924	-0.511	5.338	-2.150	-3.447	0.856	<0.0001	8.37
Heading‡	12.711	-8.722	-1.060	0.757	7.327			0.960	<0.0001	5.00

† The best six-variable linear regression model: $R_{\lambda1}$, reflectance at 757 nm; $R_{\lambda2}$, reflectance at 1846 nm; $R_{\lambda3}$, reflectance at 1937 nm; $R_{\lambda4}$ reflectance at 1727 nm; $R_{\lambda5}$, reflectance at 1963 nm; $R_{\lambda6}$, reflectance at 1686 nm.

‡ The best four-variable linear regression model: $R_{\lambda1}$, reflectance at 517 nm; $R_{\lambda2}$, reflectance at 974 nm; $R_{\lambda3}$, reflectance at 929 nm; $R_{\lambda4}$, reflectance at 541 nm.

The impact of leaf folder infestations on the spectral reflectance of rice plants grown in the active tillering and the heading stages of the second cropping season in 2001 was further evaluated by using the MLR approach. Reflectance of narrow bands from the measured spectral domain of each infestation rankings were all used as inputs for MLR analyses. Results showed that with reflectance of six narrow bands as input parameters, R^2 was promoted to 0.856 ($P<0.0001$) in the active tillering stage, while R^2 was improved to 0.960 ($P<0.0001$) with four parameters in the heading stage (Table 3). Obviously the MLR models combining spectral reflectance from more than two wavebands not only provided flexibility in choosing the individual narrow bands (Yang and Chen, 2004) but also exhibited a greater sensitivity to phenological variation of leaf folder–infested plants and improved the models' ability to estimate pest infestations.

As observed in nature and in this study, discoloration of leaves is one of the first indications of pest occurrence in rice plant. When plants are suffering from pests attacks, there are changes in leaf structure and color, providing a good indication of pest infestation. Results further indicate that spectral bands across the visible and infrared region are useful for monitoring differences in the conditions of rice infested by brown planthoppers and leaf flolder. The spectral characteristics selected in this study have shown their potential in discriminating the rankings of pest infestations. In practical applications, however, the filed spectral response remotely sensed from air-borne and space-borne platforms may be rather different than those from the ground truth. Further studies are required to link the gaps between ground-based remote sensing and real world conditions. Besides, such relationships may vary qualitatively and quantitatively during the growing season as plants age and may be influenced by the conditions of the atmosphere and the viewing geometry of detectors (Asner, 1998; Goel, 1988; Gerstl, 1990; Myneni and Asrar, 1993; Meyer *et al.*, 1995).

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